REVIEW
ATMOSPHERIC PHYSICS

Earth and Planetary Physics
2: 276–291, 2018
doi: 10.26464/epp2018026

The FGOALS climate system model as a modeling tool for supporting climate sciences: An overview

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Abstract: Climate system models are useful tools for understanding the interactions among the components of the climate system and predicting/projecting future climate change. The development of climate models has been a central focus of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG/IAP) since the establishment of the laboratory in 1985. In China, many pioneering component models and fully coupled models of the climate system have been developed by LASG/IAP. The fully coupled climate system developed in the recent decade is named FGOALS (Flexible Global Ocean-Atmosphere-Land System Model). In this paper, an application-oriented review of the LASG/IAP FGOALS model is presented. The improved model performances are demonstrated in the context of cloud-radiation processes, Asian monsoon, ENSO phenomena, Atlantic Meridional Overturning Circulation (AMOC) and sea ice. The FGOALS model has contributed to both CMIP5 (Coupled Model Intercomparison Project-phase 5) and IPCC (Intergovernmental Panel on Climate Change) AR5 (the Fifth Assessment Report). The release of FGOALS data has supported the publication of nearly 500 papers around the world. The results of FGOALS are cited ~106 times in the IPCC WG1 (Working Group 1) AR5. In addition to the traditional long-term simulations and projections, near-term decadal climate prediction is a new set of CMIP experiment, progress of LAGS/IAP in the development of near-term decadal prediction system is reviewed. The FGOALS model has supported many Chinese national-level research projects and contributed to the national climate change assessment report. The crucial role of FGOALS as a modeling tool for supporting climate sciences is highlighted by demonstrating the model's performances in the simulation of the evolution of Earth's climate from the past to the future.

Keywords: Climate system model; FGOALS; Climate variability; climate change

Citation: Zhou T. J., Wang B., Yu Y. Q., Liu Y. M., Zheng W. P., Li L. J., Wu B., Lin P. F., Guo Z., ... and Zhang W. X. (2018). The FGOALS climate system model as a modeling tool for supporting climate sciences: An overview. *Earth Planet. Phys.*, *2*(4), 276–291. http://doi.org/10.26464/epp2018026

1. Introduction

The climate system is an interactive system consisting of the atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Addressing the interplay of physical, chemical, and biological processes among the above components or predicting/projecting the climate system's response to changes in anthropogenic forcing agents requires a coupled climate-system model approach. Recognizing the central importance of climate models in climate variability, climate prediction, and climate change studies, the development of climate models has been a central focus of research activities of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (hereinafter LASG/IAP) since the establishment of the laboratory in 1985. In past decades, great achievements have been made by LASG/IAP in the development of coupled climate models (see Figure1 for the family tree of ocean-atmosphere coupled models developed in LASG/IAP), as evidenced by the establishment of the pioneering version of the Chinese coupled climate system model named GOALS (Global Ocean Atmosphere Land System Model) (*see monograph* edited by Zhang XH et al., 2000) and a later version named FGOALS (the Flexible Global Ocean–Atmosphere–Land System Model) (*see monograph* edited by Zhou TJ et al., 2014c).

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Received 28 JUN 2018; Accepted 17 JUL 2018.
Accepted article online 30 JUL 2018.

Both the GOALS and FGOALS models have played crucial roles in climate variability and climate change studies. The models have been actively applied in many international projects organized and coordinated by the climate modeling community, including the comparative model calculations in the context of the CMIP (the Coupled Model Intercomparison Project) (*see* Guo YF et al., 2001; Yu YQ et al., 2004; Zhou TJ et al., 2007; Yu YQ et al., 2008; Yu

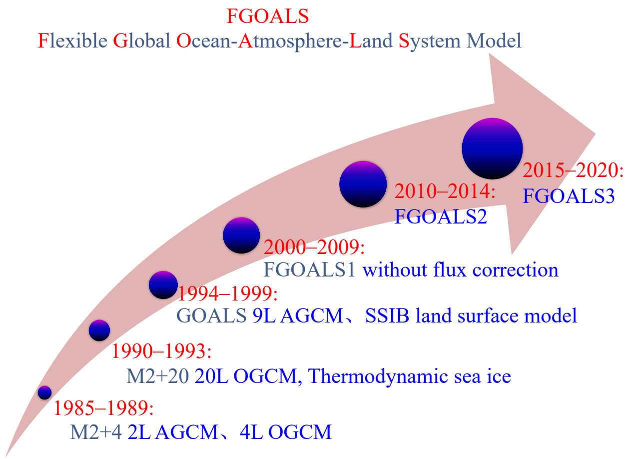

Figure 1. The history of ocean-atmosphere coupled model development in LASG/IAP.

YQ, 2014 and Zhou TJ et al., 2014a for reviews). The CMIP was promoted by the Working Group on Coupled Modeling (WGCM) of the World Climate Research Program (WCRP). The fifth phase of the CMIP (CMIP5) aims to provide a multi-model context for "*assessing the mechanisms responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds; examining climate predictability and exploring the predictive capabilities of forecast systems on decadal time scales; and more generally, determining why similarly forced models produce a range of responses*" (Taylor et al., 2012). The outputs of CMIP5 models are important resources for the international climate research community in enhancing our understanding on the fundamental mechanisms underpinning the interactions among the coupled climate system. The past climate simulations, detections, and attributions of observed climate changes, near-term decadal climate predictions, and scenario-based climate projections organized by CMIP5 have provided useful bases upon which scientific questions relevant to anthropogenic climate change were addressed as part of the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5). In addition to their application in the CMIP, the models developed by LASG/IAP have been widely used by the Chinese climate research community in the implementation of many national projects, such as the National Program on Key Basic Research Projects and the projects of the National Natural Science Foundation of China, among many others.

The motivation of this paper is to provide an application-oriented review of the FGOALS model. The contributions of the FGOALS climate system model to CMIP5 and some Chinese major basic research projects are summarized. The crucial role of the FGOALS model in understanding the mechanisms of the evolution of Earth's climate is reviewed.

2. Overview of the CMIP5 Version of FGOALS

The model version involved in CMIP5 is FGOALS2, which has two sub-versions, namely, FGOALS-s2 and FGOALS-g2. They share the same coupling framework and ocean and land components but adopt different atmospheric and sea ice components (See Table 1 for the configurations of the two versions). Detailed information on FGOALS-g2 and FGOALS-s2 can be found in Li LJ et al., (2013a, b) and Bao Q et al., (2013), respectively. Instead of presenting a technical review of the CMIP5 version of FGOALS, we summarize major improvements in model performance in the context of cloud-radiation processes. Asian monsoon ENSO phenomena, and Atlantic Meridional Overturning Circulation (AMOC), the performance of which was a major weakness of the former model version, which was named FGOALS1 (Yu YQ et al., 2011).

Table 1. Comparison of FGOALS-s2 and FGOALS-g2 versions for CMIP5

Components	FGOALS-s2	FGOALS-g2
Atmospheric model	SAMIL2	GAMIL2
Oceanic model	LICOM2	LICOM2
Land model	CLM3	CLM3
Sea ice model	CSIM5	CICE4-LASG
Flux coupler	CCSM Coupler-6	CCSM Coupler-6

2.1 Improvement of Cloud Distribution and Cloud Radiation

The atmospheric component of FGOALS-g2 is GAMIL2. The geographical distribution of total cloud fraction is reasonably reproduced by GAMIL2, with the maximum concentrations in the tropical and mid-latitude storm tracks (Figure 2). Compared with the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), GAMIL2 results prove to be underestimations in most places, GAMIL2 values having a global mean of 0.61 versus 0.69 from actual observations (Li LJ et al., 2014a). Note that the global averaged total cloud fractions are 0.43 and 0.51 in the Community Atmosphere Model (CAM) versions 4 and 5, respectively, when using the CALIPSO simulator (Kay et al., 2012). Underestimation in the cloud fraction is a common model bias in most CMIP3 and CMIP5 models (e.g., Dolinar et al., 2015).

The underestimations are particularly evident in most stratiform cloud regions, such as the subtropical ocean, North Pacific, North Atlantic, and circumpolar ocean (Pincus et al., 2008; Wu GX et al., 2012). GAMIL2 improves the representation of low-level stratiform clouds, especially at mid and high latitudes (Figure 3). This improvement is due to GAMIL2's linear fitting of satellite cloud fraction and estimated inversion strength (Wood et al., 2006) to improve the stability-based diagnostic stratiform scheme, in which the effect of free-tropospheric stratification changes has been removed from the lower troposphere stability. This treatment also enhances the sensitivity of cloud to sea surface temperature changes, which leads to better performance in simulating the cloud radiative forcing interannual variability (Guo Z and Zhou TJ, 2014).

With the improvement of cloud fraction simulations, the shortwave and longwave cloud radiative forcing (S/LWCF) in GAMIL2 has correspondingly been improved. The global averaged SWCF is –48.2 W·m^{-2} in GAMIL2, very close to both the Clouds and the Earth's Radiant Energy System (CERES)-Energy Balanced and Filled (EBAF) value (–48.6 W·m^{-2}) and the CMIP5 multimodel mean (–49.2 W·m^{-2}) (Li LJ et al., 2013a; Dolinar et al., 2015). Their near

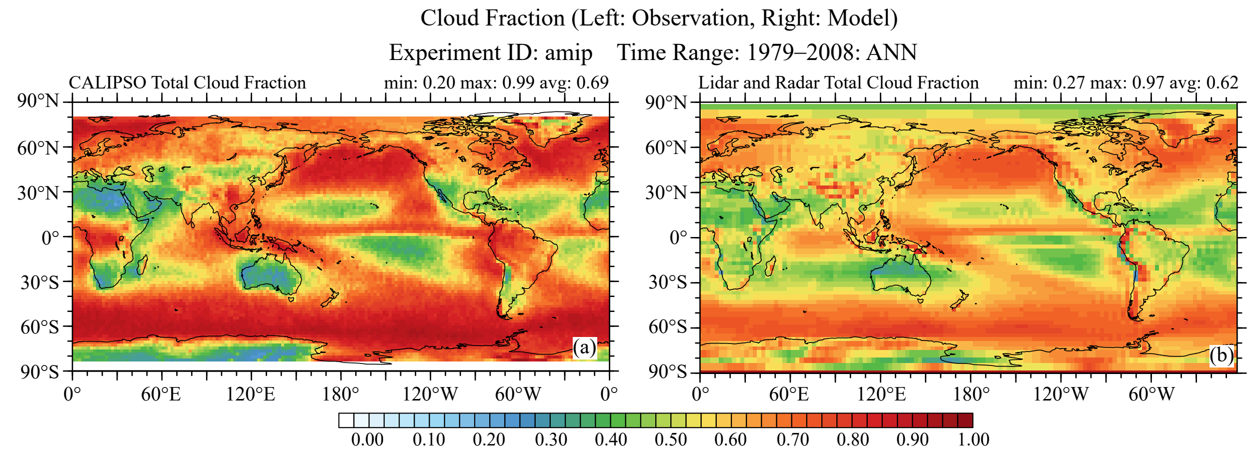

Figure 2. Geographical distribution of total cloud fraction for (a) CALIPSO observations and (b) GAMIL2 using the CALIPSO satellite simulator (from Li LJ et al., 2014a) .

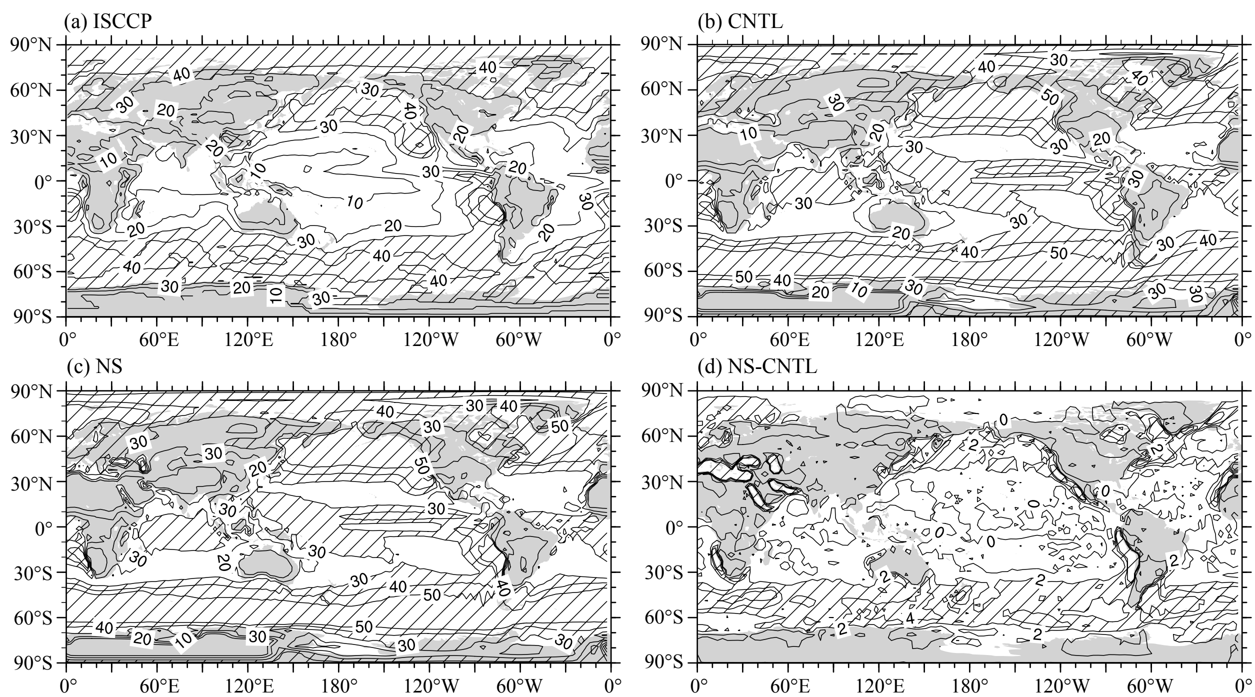

Figure 3. Annual mean low-level stratiform cloud fraction (%). (a) ISCCP; (b) GAMIL2 with original stratocumulus scheme; (c) GAMIL2 with a modified stratocumulus scheme; (d) Differences in cloud amount between (b) and (c).

global (65°S–65°N) means and geographic distributions are shown in Figure 4. In addition to improvement to the mean state, the SWCF response/feedback to SST anomaly has been improved in GAMIL2 and FGOALS-g2 (Li LJ et al., 2014b, 2015). The FGOALS-g2 model, as one of the four CMIP5 representative models, has been used to study the cloud and precipitation responses to warming (Stevens and Bony, 2013).

2.2 Improvement of ENSO Simulation

ENSO is the robust interannual variability phenomenon of the coupled ocean-atmosphere system. It is one of the most important observational metrics for model evaluation. Compared with the version g1.0 of FGOALS (hereafter referred to as FGOALS-g1.0) both FGOALS-g2 and FGOALS-s2 show better performance in ENSO simulations (Figure 5). In particular, FGOALS-g2 is one of the best climate models to reproduce ENSO behaviors, including amplitude, periodicity, and dynamic and thermodynamic feedbacks, in CMIP5 models (Bellenger et al., 2014). The improved ENSO simulations by FGOALS-g2 and FGOALS-s2 are mainly attributed to cloud-shortwave radiation forcing feedback and thermocline feedback (Yu YQ et al., 2013; Chen L et al., 2013). The former results from sub-grid scale parameterization schemes in the atmospheric component, and the latter is due to better simulation of equatorial thermocline depth in the oceanic component (Chen L et al., 2016).

In addition to improving ENSO simulation, both FGOALS-g2 and

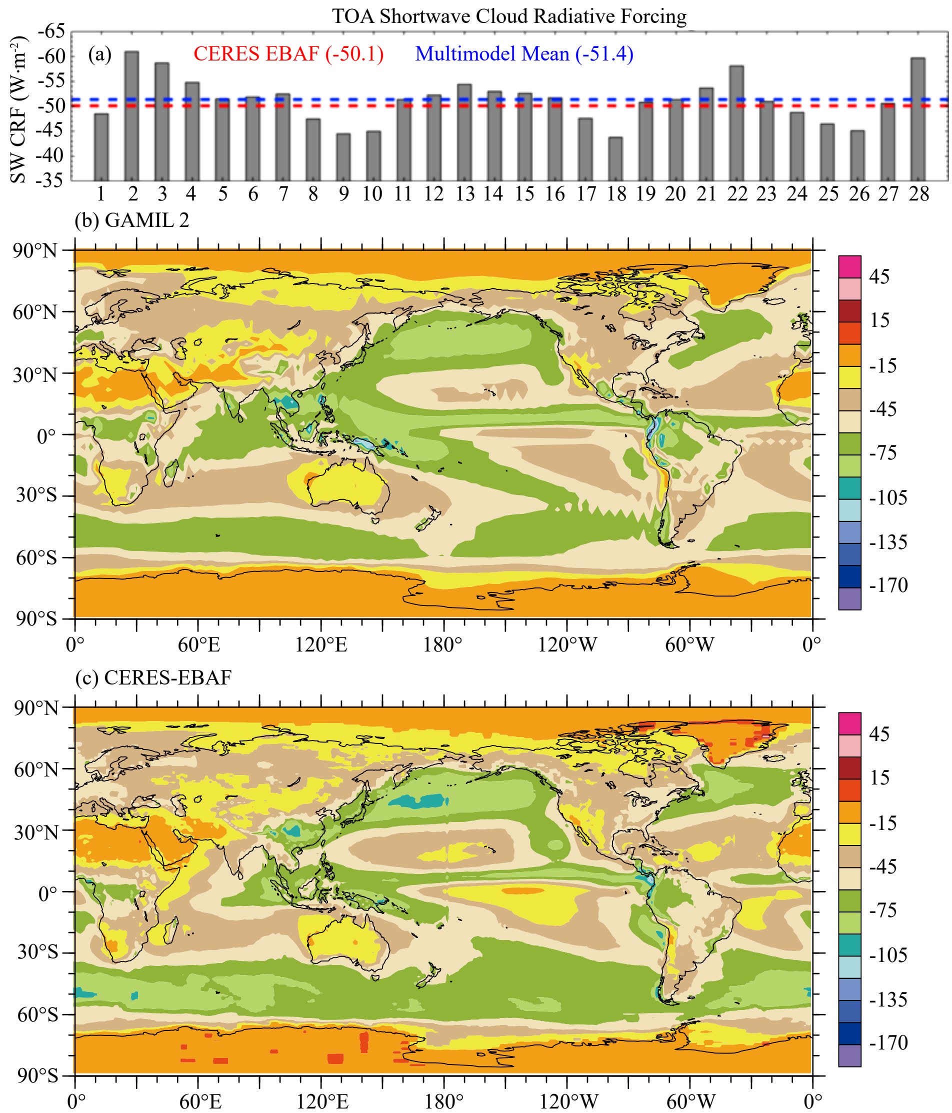

Figure 4. (a) Near global (65°S–65°N) mean shortwave cloud radiations forcing at the top of the atmosphere from 28 CMIP5 models, multimodel mean (blue) and satellite observation (red) CERES EBAF, and the geographical distribution for GAMIL2 (b) and CERES EBAF (c). Model number 11 is GAMIL2. (Figure (a) from Dolinar et al., 2015; Figures (b) and (c) redrawn based on Li LJ et al., 2013a).

FGOALS-s2 simulate more reasonable seasonal cycles in the equatorial Pacific than does FGOALS-g1.0 (Figure 6). The observed SST is characterized by an annual cycle in the eastern equatorial Pacific and a semi-annual cycle in the western equatorial Pacific. The former cycle is driven by meridional wind across the equator, and the latter is driven by solar radiation, both of which can be well reproduced by FGOALS-g2 and FGOALS-s2 but are poorly simulated by FGOALS-g1.0 which suffers from larger double-ITCZ biases than the other two versions, leading to a lack of climatological mean meridional wind across the equator in FGOALS-g1.0 (Yu YQ et al., 2013).

2.3 Improvement of the Asian Monsoon

Due to the impacts of complex orography and land-sea thermal contrast, simulation of the Asian monsoon has been a challenge for climate models (Sperber et al., 2013; Zhou TJ et al., 2016, 2017). FGOALS2 is particularly successful at simulating the Asian summer monsoon. For monsoon climatology, both the stand-alone atmospheric models of FGOALS2 (SAMIL and GAMIL) reproduce the western North Pacific monsoon trough and southerly component associated with the East Asian summer monsoon (EASM), showing significant improvement over the old version of FGOALS for CMIP3 (Liu YM et al., 2013; Song FF and Zhou TJ, 2014a; Zhou TJ et al., 2014b; Zou LW and Zhou TJ, 2015). Driven by historical SST, both SAMIL and GAMIL can simulate the temporal evolution of the EASM, for which GAMIL has achieved the highest correlation score in all of the CMIP5 models.

The key anomalous circulation associated with the interannual variability of the EASM is the western North Pacific anomalous anticyclone (WPAC), which corresponds to enhanced precipitation extending from the middle and lower reaches of the Yangzi River to the south of Japan during an El Niño decaying summer (Zhang RH et al., 1996; Chang CP et al., 2000; Wang B et al., 2000; Li T et al., 2017). The WPAC is coupled with the warm SST anomalies in the tropical Indian Ocean through atmospheric Kelvin waves (Yang JL

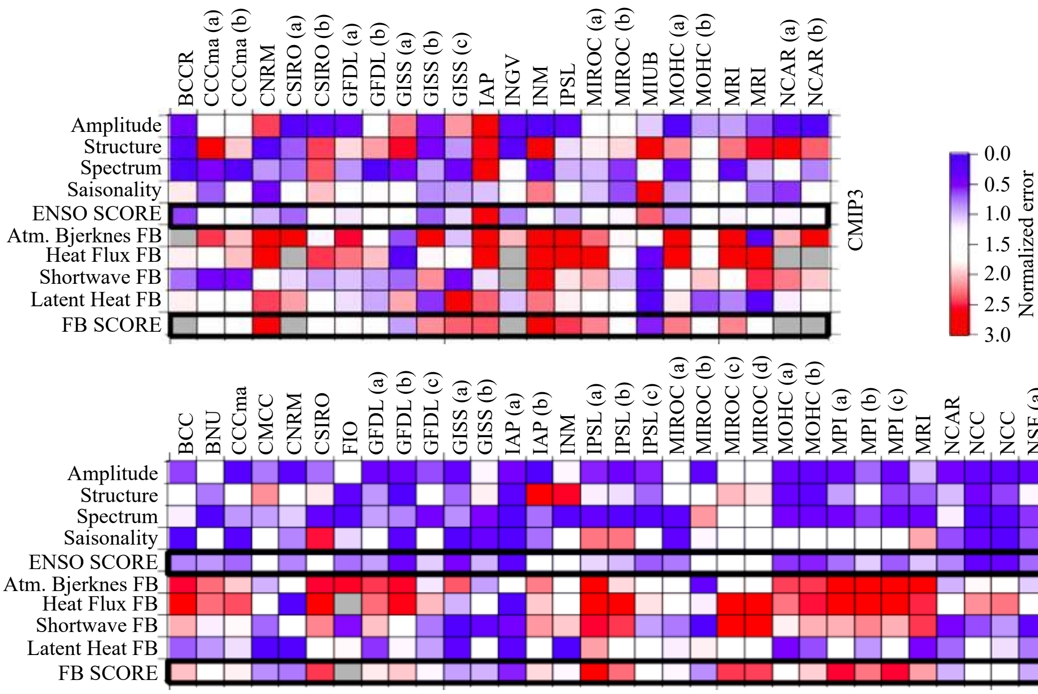

Figure 5. ENSO skills in CMIP3 and CMIP5 models (Figure 13 from Bellenger et al. (2014)).

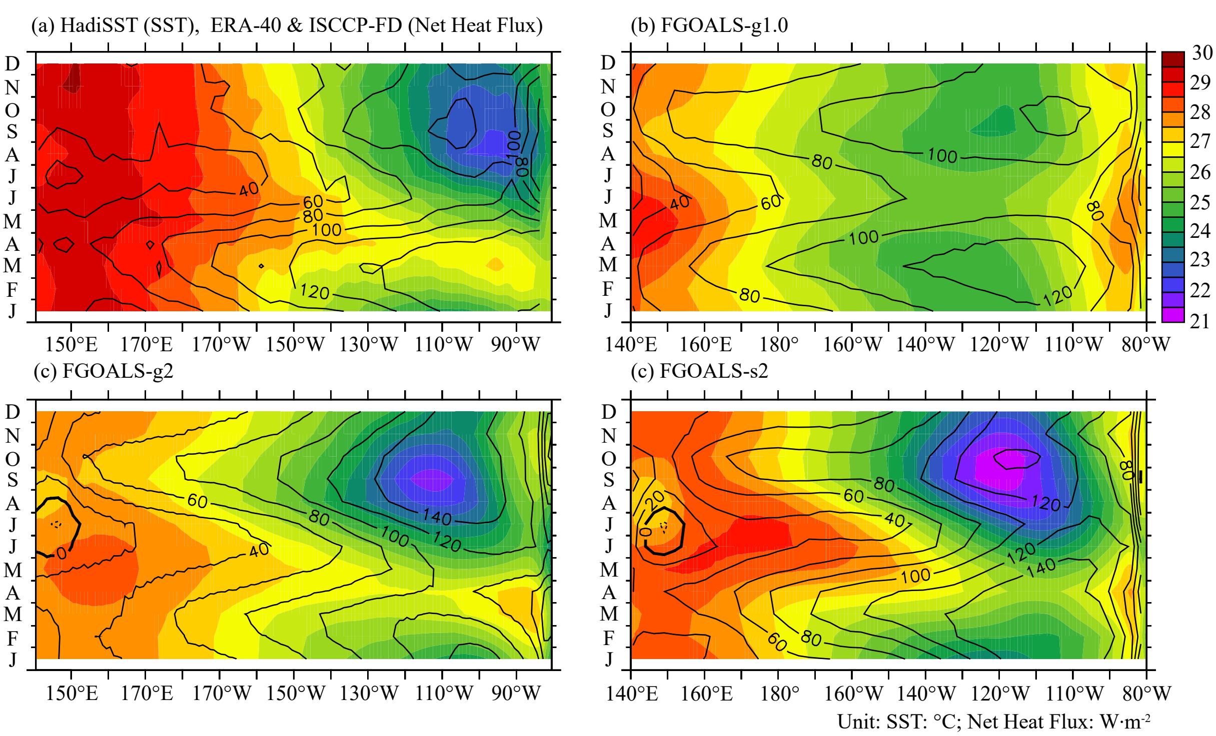

Figure 6. Seasonal cycle of SST (°C; shaded) and net heat flux (W·m^{-2}; contour) averaged between 2°N and 2°S along the equator in the Pacific Ocean from (a) observations, (b) FGOALS-g1.0, (c) FGOALS-g2, and (d) FGOALS-s2 (Figure 2 from Yu YQ et al. (2013)).

et al., 2007; Wu B et al., 2009); this coupling is referred to as the Indian Ocean-WPAC teleconnection pattern (Song FF and Zhou TJ, 2014a). Both SAMIL and GAMIL are highly successful in simulating the Indian Ocean-WPAC teleconnection (Figure 7), which leads to improvements in the simulation of interannual variability of the EASM (Hong JL and Liu YM, 2012; Song FF and Zhou TJ, 2014a). Compared with stand-alone atmospheric models, coupled models in CMIP5 (including FGOALS-g2 and FGOALS-s2) show improved performance in simulating the Indian Ocean-WPAC teleconnection pattern, partly due to overestimated warm SST anomalies over the eastern tropical Indian Ocean, which tends to amplify the signals (Song FF and Zhou TJ, 2014b).

The WPAC is established during an El Niño mature winter (Figure 8a, b). It is asymmetric with its counterpart, the western Pacific anomalous cyclone (WPC), which is established during a La Niña mature winter (Figure 8c, d; Wu B et al., 2010). The circulation asymmetry contributes to the asymmetry in the southern component of the East Asian winter monsoon between El Niño and La Niña

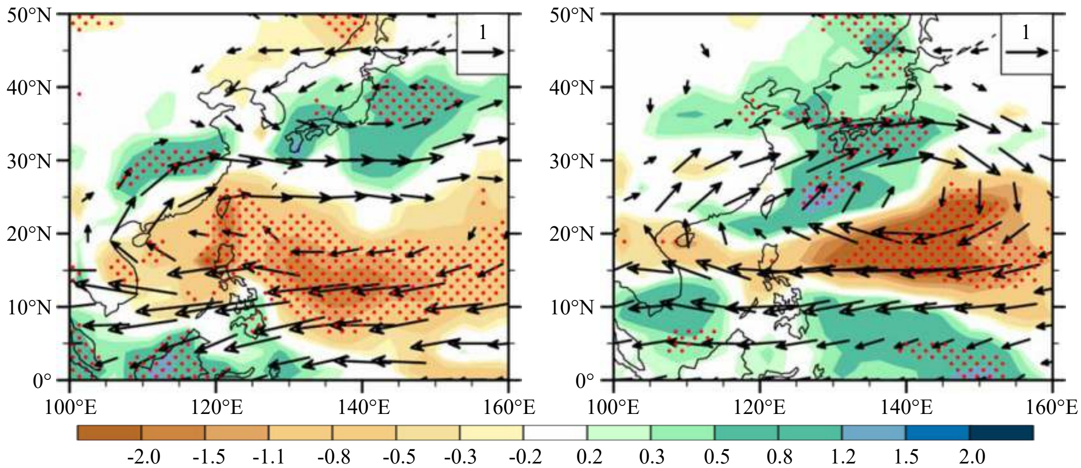

Figure 7. East Asian summer monsoon in El Niño decaying summer derived from reanalysis (left) and FGOALS-s2 simulation (right, redrawn based on Song FF and Zhou TJ, 2014a).

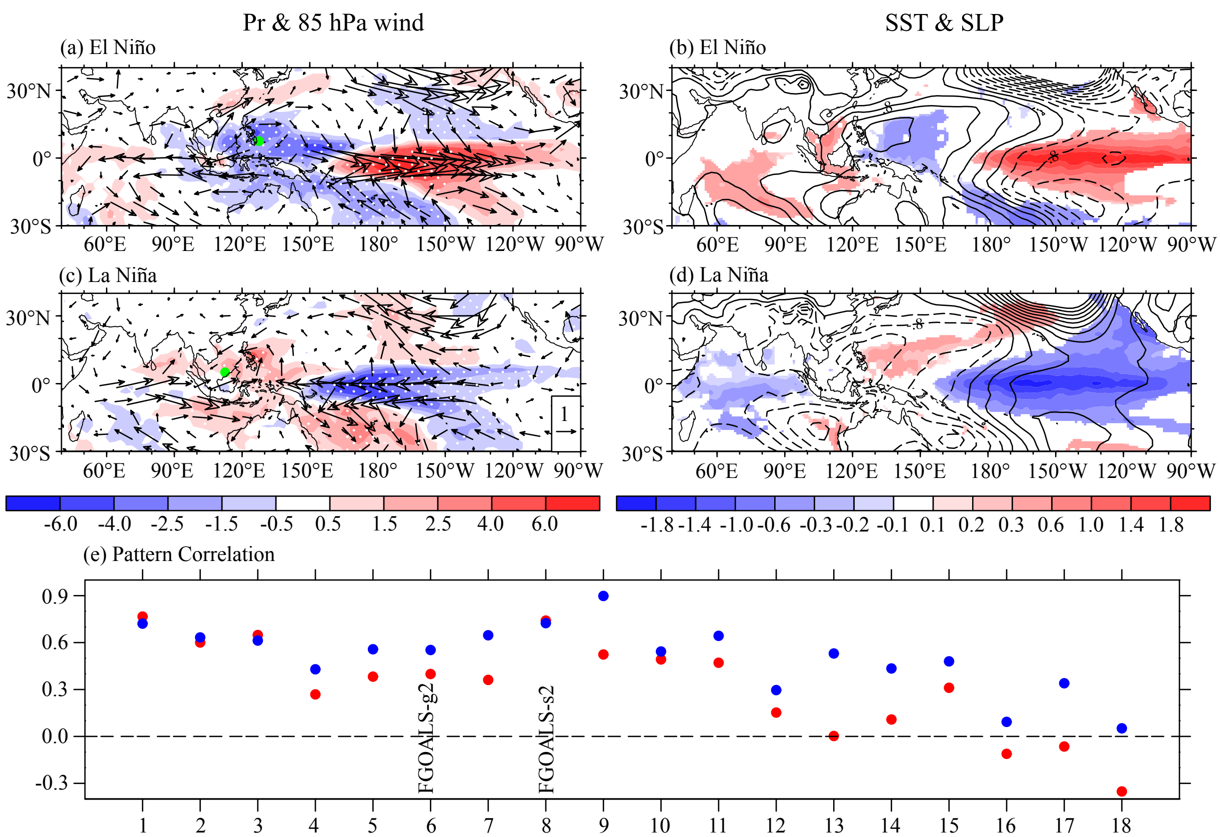

Figure 8. (a–d) Observational composite maps for El Niño and La Niña mature winter. (a, c) Precipitation (shading, unit: mm day^{-1}) and 850 hPa wind anomalies (vectors, unit: m s^{-1}). Precipitation anomalies exceeding the 5% significance level are dotted. Green dots represent the centers of the WPAC (a) and WPC (c), which are defined as the local extremes of the stream function anomalies. (b, d) are the same as (a, c) except they show SST (unit: K) and SLP anomalies (unit: hPa). Solid (dashed) lines denote positive (negative) values. Contour intervals are 0.4 hPa. Only those SST anomalies with statistical significance at the 5% level are shown. (e) Evaluation of CMIP5 models in simulating the WPAC and WPC during ENSO mature winter. The skill is measured through pattern correlations of the composite maps of 850 hPa vorticity anomalies in the WNP (0°–25°N, 120°E–150°E) between the observation and each model. Red and blue dots represent El Niño and La Niña, respectively. Models 6 and 8 are FGOALS-g2 and FGOALS-s2, respectively (after Wu B and Zhou TJ, 2016).

(Guo Z et al., 2017). Both FGOALS-s2 and FGOALS-g2 can reproduce the WPAC and WPC during ENSO mature winter and their asymmetric features. FGOALS-s2 is one of the best CMIP5 models in this regard (Figure 8e; Wu B and Zhou TJ, 2016).

Because of the excellent performance of FGOALS-s2 in simulating the WPAC, it was used to conduct Pacific pacemaker experiments to investigate the mechanisms responsible for the maintenance of the WPAC during the El Niño mature winter and the following spring (Wu B et al., 2017a, b). It was proposed that the WPAC is maintained by the moist atmospheric teleconnection from the equatorial central-eastern Pacific through a wind-moist enthalpy advection mechanism. This new mechanism is a pure internal atmospheric process and is completely different from the conventional mechanism, which emphasizes the central role of the local air-sea interactions (Wang B et al., 2000).

2.4 Improvements of AMOC and Sea Ice

AMOC transports large amounts of heat from low latitudes to high latitudes. One major weakness of FGOALS1 is the reproduction of AMOC, which is almost absent (Yu YQ et al., 2011; Lin PF et al., 2013a). In FGOALS2, the simulated AMOC maximal magnitudes are improved and closer to the observed value at 26.5°N from the RAPID Climate Change Programme (RAPID) (http://www.rapid.ac.uk/) (Figure 9). The AMOC values obtained with FGOALS2 are comparable with those from the other CMIP5 simulations. The maximal magnitudes simulated by FGOALS2 were located at the depth of 1000 m (Lin PF et al., 2013a, b), where the observations are located (Lumpkin and Speer, 2007). The improvement of AMOC results from enhanced mixing due to the new oceanic mixing scheme. A stronger AMOC will lead to large heat transport to the subpolar region (Lin PF et al., 2013a, b) and reduce SST cold biases there.

Associated with the improvement of SST biases in the subpolar region, the sea ice extent (SIE, i.e., 15% of sea ice concentration) distributions and seasonal variations (boreal winter and summer are denoted by February and September, respectively) are more realistic in FGOALS2 in the Northern Hemisphere than in FGOALS1, although the values in boreal winter (summer) are slightly smaller (larger) than the observed values. In the Southern Hemisphere, the SIE distributions and seasonal variations are comparable to the observed values. However, the SIEs were overestimated in all seasons (Lin PF et al., 2013b, c).

3. Contributions to CMIP5 and IPCC AR5

There is a long history of LASG/IAP contribution to the Coupled Model Intercomparison Project. The LASG/IAP model participated in the first phase of the CMIP in 1990 and ultimately contributed to five successive phases of the CMIP (Zhou TJ et al., 2014a, b). The evaluation and interpretation of model simulations have been cited by each previous IPCC Assessment Report and have provided scientific bases for policy makers. In the ~20-year his-

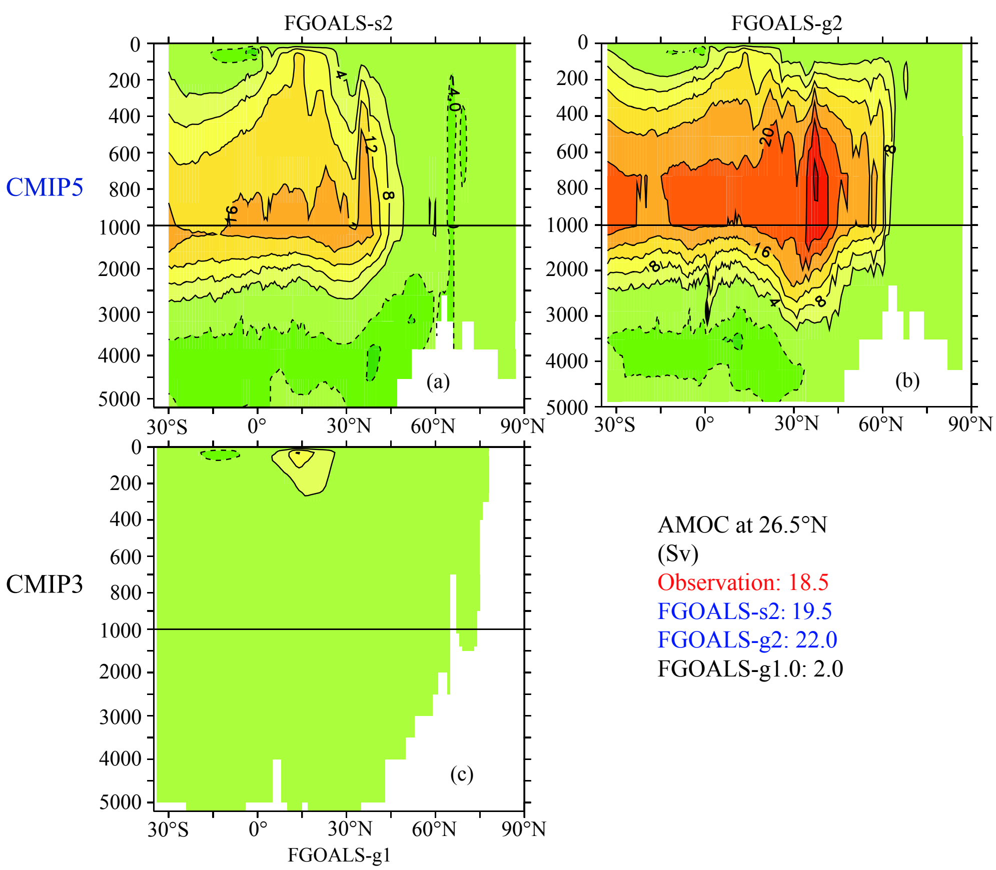

Figure 9. AMOC (Sv, 1 Sv=10^6 m^3/s) simulated by FGAOLS versions for CMIP3 and CMIP5. The AMOCs at 26.5°N for CMIP5, CMIP3 versions and RAPID data are shown (after Lin PF et al., 2013a).

tory of the CMIP, there are only nine models worldwide that have participated in all phases of the CMIP, and FGOALS is one of them.

The latest phase of the CMIP is named CMIP5. The outputs of CMIP5 experiments have been fed into the IPCC WG1 Fifth Assessment Report (AR5). CMIP5 includes two types of climate change modeling experiments: long-term integrations and near-term integrations. The long-term integrations represent century timescales, whereas the near-term integrations, also known as decadal prediction experiments, provide near-term decadal prediction. In LASG/IAP, both the long-term and short-term experiments were performed with FGOALS2, with topics ranging from the paleoclimate to future projections and including pre-industrial control simulation, historical simulation, three paleoclimate simulations of three periods, decadal predictions, Representative Concentration Pathways (RCP) scenarios projections, and sets of CO_2-related sensitivity experiments (See Table 2 for a list of FGOALS CMIP5 experiments). Among these simulations, three paleoclimate simulations also contributed to the third phase of the Paleoclimate Modeling Intercomparison Project (PMIP3).

The model integrations of all of the FGOALS CMIP5 simulations exceed 6000 model years, with more than 50 Terabytes of data. All of the simulations were published through the ESG nodes in LASG/IAP to fulfill the goal of freely open access to scientists all over the world. As of the end of year 2015, the data traffic had reached 270 Terabytes, and the downloaded data were widely and internationally used and analyzed in fields such as climate change, air-sea interactions, etc. By the end of 2014, more than 478 papers had been published internationally that are partly based on the data of FGOALS (refer to Figure 10).

The FGOALS CMIP5 simulations have contributed to the IPCC WG1AR5. According to our calculations, results of FGOALS are cited 106 times in the IPCC WG1 AR5. There are 53 papers co-authored by LASG/IAP scientists that are cited in the IPCC WG1 AR5. As shown in Figure 10, these papers cover the topics of model evaluation, paleoclimate simulation, detection and attribution of

Table 2. Overview of FGOALS CMIP5 experiments

No.	Experiment description	CMIP5 label	FGOALS-g2	FGOALS-s2
1	Preindustrial control run	piControl	1	1
2	Past ~1.5 centuries (1850–2005)	historical	5	3
3	AMIP run (observed SSTs and sea ice prescribed for 1979–present)	amip	1	3
4	Future projection (2006–2300) forced by RCP4.5	rcp45	1	3
5	Future projection (2006–2300) forced by RCP8.5	rcp85	1	3
6	Future projection (2006–2300) forced by RCP2.6	rcp26	1	1
7	Future projection (2006–2100) forced by RCP6	rcp60	–	1
8	Benchmark 1% $year^{-1}$ increase in CO_2 (to quadrupling)	1pctCO_2	1	1
9	Quadruple CO_2 abruptly, then hold fixed	abrupt4×CO_2	1	1
10	Climatological SSTs and sea ice imposed from piControl	sstClim	2	1
11	As in sstClim, but with 4×CO_2 imposed	sstClim4×CO_2	1	1
12	As in AMIP, but with radiation code seeing 4×CO_2	amip4×CO_2	1	–
13	Patterned SST anomalies added to AMIP conditions (as called for by CFMIP)	amipFuture	1	–
14	Zonally uniform SSTs imposed on an ocean-covered Earth (as called for by CFMIP)	aquaControl	1	1
15	As in aquaControl, but with 4×CO_2	aqua4×CO_2	1	2
16	As in aquaControl, but with a uniform 4 K increase in SST	aqua4K	1	1
17	As in AMIP, but with a uniform 4 K increase in SST	amip4K	1	–
18	Historical simulation but with natural forcing only	historicalNat	1	–
19	Historical simulation but with GhG forcing only	historicalGHG	1	–
20	Historical simulation but with other individual forcing agents or combinations of forcings	historicalMisc	2	–
21	Mid-Holocene conditions (as called for by PMIP)	midholocene	1	1
22	Last glacial maximum conditions (as called for by PMIP)	lgm	1	1
23	Decadal hindcasts/predictions	decadalxxxx	3	3
24	Decadal hindcasts/predictions extended to 30 year	decadalxxxx	3	3
25	Natural forcing for 850–1850 (as called for by PMIP)	Past1000	1	1

Note: * The ensemble members for individual model simulation are shown in the right columns.

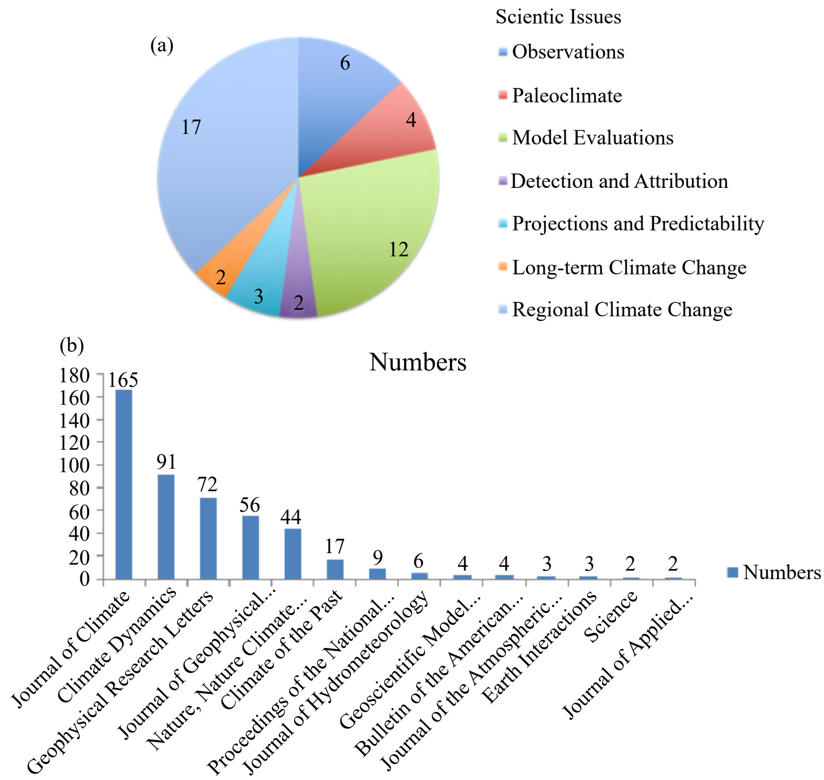

Figure 10. (a) Number of papers led by LASG/IAP scientists cited by the IPCC WG1 AR5; (b) Distribution of papers that used FGOALS model data among journals.

anthropogenic historical climate change, and climate projection. The data of FGOALS were crucial to these investigations. The data of FGOALS have also contributed to the 2nd and 3rd National Climate Change Assessment reports of China.

In addition to traditional long-term simulations, near-term decadal climate prediction is part of a new set of experiments designed by WGCM for CMIP5. Decadal climate prediction (DCP) experiments focus on climate change in the future 10–30 years and are among the two core sets of experiments of CMIP5 (Taylor et al., 2012). The DCP experiments were conducted by using both FGOALS-g2 and FGOALS-s2. The results of both have been submitted to CMIP5 and cited by the IPCC AR5 (Kirtman et al., 2013). On decadal time scales, the climate system is modulated by both internal variability and external forcing (Meehl et al., 2009). Here, internal variability mainly refers to variability generated by air-sea interactions, such as ENSO, the Pacific decadal oscillation (PDO), and the Atlantic multidecadal Oscillation (AMO) (Meehl et al., 2009), which are very sensitive to initial states. Hence, initialization is of key importance in DCP experiments (Meehl et al., 2014), which include a long cycle of assimilation. The DCP experiments of FGOALS-g2 and FGOALS-s2 were based on two different initialization schemes.

For FGOALS-g2, a nudging-based three-dimensional variational data assimilation scheme was proposed (Wang B et al., 2013). Full-field observations were incorporated into the initial conditions of the ocean component model at each integration step; this approach differs from the commonly used nudging scheme in which model errors are reduced directly using full-field or anomaly observations. Initializing the prediction model with full-field observations may lead to drifts in decadal predictions from the observed state at the initial time toward an imperfect model climate state at the prediction time. In this case, bias corrections are necessary for decadal predictions. The existing bias corrections are mostly post-processing corrections; i.e., the prediction results are corrected after the predictions are complete. These correction schemes may not reduce the impacts of model bias on anomaly predictions during the prediction procedure. For this reason, a dynamical bias correction scheme was developed (Wang B et al., 2013), which reduces the bias in initial conditions at each integration step during the predictions so that the possible influences of the initial bias on anomaly predictions, as well as the drifts caused by full-field initialization, are alleviated.

The initialization scheme designed for FGOALS-s2 was referred to as the incremental analysis update (IAU) scheme (Wu B and Zhou TJ, 2012; Wu B et al., 2015). The scheme assimilates the gridded observational ocean temperature and salinity data. Different from the conventional nudging scheme, the IAU gradually introduces calculated analysis incrementally into the model as a fixed forcing term during an assimilation cycle (Bloom et al., 1996).

The standard DCP experiments include a series of ten-year-long hindcast runs started once every five years to evaluate the predictive skill of prediction systems. Systematic evaluation of the hindcast runs indicates that the DCP experiments of both FGOALS-s2 and FGOALS-g2 show higher predictive skill for decadal variability of SST and surface air temperature (SAT) than their corresponding historical simulations for 20th-century climate (HIST experiments) without initializations. For FGOALS-g2, the improvement is mainly in the prediction of SST in the equatorial central-eastern Pacific and SAT in China (Wang B et al., 2013). For FGOALS-s2, the improvement is mainly in the prediction of SST in the warm pool region and North Atlantic (Wu B et al., 2015). Even after removing the long-term trend due to GHGs-induced global warming, the DCP experiments of FGOALS-s2 can reproduce the AMO with accuracy comparable to that of most CMIP5 models (Doblas-Reyes et al., 2013).

Both the HIST and DCP experiments convincingly track global warming, using the same external forcing, but the former overestimate the warming. The DCP experiments of both FGOALS-g2 and FGOALS-s2 present warming closer to observations. The better performance of the DCP experiments is partly due to the more realistic initial conditions provided by their initialization runs (Wang B et al., 2013; Wu C et al., 2015).

4. Support to Chinese National Research Projects and Beyond

4.1 Support of the FGOALS Model to National-Level Research Projects

The FGOALS model is a useful modeling tool that allows researchers to conduct fundamental research into the Earth's past, present, and future climates. It has played an active role in promoting interdisciplinary climate research in China. To date, the model has been widely used in studies of multi-scale variability of the climate system, ocean-atmosphere interactions, changes of monsoon regimes, simulations of paleoclimate and past millennial climate, near-term climate prediction, and long-term climate projections. It has been used by the Chinese climate research community in the implementation of many national-level projects, such as the National Program on Key Basic Research Project ("973 project"), the National High Technology Research and Development Program ("863 project"), the Knowledge Innovation Program of the Chinese Academy of Sciences, the Strategic Priority Research Program of the Chinese Academy of Sciences, the Public Science and Technology Research Funds Projects of Meteorology, the Public Science and Technology Research Funds Projects of Ocean, and the projects of the National Natural Science Foundation of China, among many others. As shown in Figure 11, more than 16 National Program on Key Basic Research Projects have employed the FGOALS model as a modeling tool. The model has also contributed to two projects of the Strategic Priority Research Program of the Chinese Academy of Sciences. LASG/IAP scientists have served as PIs/COIs in more than 20 national-level projects that employ FGOALS as a numerical modeling platform.

Under the umbrella of these national-level projects, some fundamental research has been performed using this modeling system. For example, based on numerical experiments of the FGOALS model, Wu GX et al. (2012) investigated the influences of the land-sea distribution and large-scale orography on the formation of the modern Asian summer monsoon system. Surface sensible heating on large mountain slopes in the summer can pump up the surrounding atmosphere to produce surface convergent flow, and

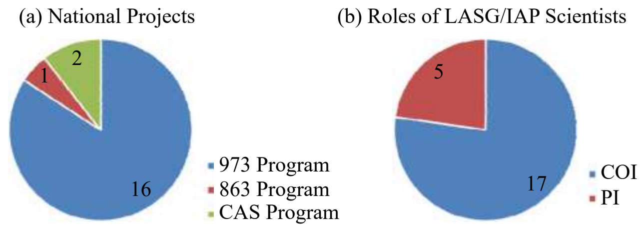

Figure 11. (a) Number of projects of the National Program on Key Basic Research Project (973), the National High Technology Research and Development Program (863), and the Strategic Priority Research Program of the Chinese Academy of Sciences (CAS) that employ FGOALS as a modeling tool. (b) Numbers of LASG/IAP scientists that serve as PIs/COIs in national-level projects that employ FGOALS as a modeling tool.

cooling in the winter can pump it down to produce divergent flow; together, these actions combine to form a sensible heat–driven pump and thereby affect monsoon circulation (Wu GX et al., 2007). The integration of the Iran Plateau into the Tibetan Plateau generated an extra cyclonic circulation in the lower troposphere, which contributes to dryness in North Africa and heavy precipitation over the Arabian Sea and northern India, enhances the Indian and East Asian summer monsoons, and spurs the development of a mid-Asia desert.

The impact of surface sensible heating over the Tibetan Plateau (SHTP) on the western Pacific subtropical high (WPSH) and East Asian monsoon was investigated based on stronger and weaker SHTP experiments (Duan AM et al., 2017). Stronger spring SHTP is usually followed by an enhanced and westward extension of the WPSH in the summer, and vice versa. Numerical experiments using both an AGCM and a CGCM confirmed that SHTP influences the large-scale circulation anomaly over the Pacific, which features a barotropic anticyclonic response over the northwestern Pacific and a cyclonic response to the south. Owing to different background circulation in the spring and summer, such a response facilitates a subdued WPSH in the spring but an enhanced WPSH in the summer, and associated moisture transports.

Another example is the support of FGOALS model to ocean science studies in China. Based on the ocean component of FGOALS2.0, LICOM, a quasi-global eddy-resolving ocean model has been developed under the support of the National Program on Key Basic Research Project, titled "The processes, mechanism and predictability of ocean dynamic environment in the North-West Pacific" (Liu HL et al. 2014). In general, with the increase of the horizontal resolution, the results of the model are significant improved in almost all aspects we investigate, including both the general oceanic circulation and mesoscale eddies, the circulations in the region of complex land-sea distribution, such as the Indonesian Seas (Liu HL et al., 2013). The results of the model have helped the project team to understand the simulation of mesoscale eddies (Feng BX et al., 2017), the transports of eddies (Lu JH et al., 2016), the energy cascade between large and mesoscales (Wang SP et al., 2018), and the mesoscale topography on the Kuroshio intrusion in Luzon Strait (Huang ZD et al., 2017), demonstrating the crucial role of the model as a numerical modeling platform in the project.

4.2 Contributions of the FGOALS Model to Understanding the Evolution of Earth's Climate Change

Climate modeling increases our understanding of the mechanisms of past climate change. Studies of the paleoclimate provide a unique opportunity to evaluate model performance as well as understand the mechanisms of climate change in different climate backgrounds (Jiang DB et al., 2015). In CMIP5, paleoclimate simulations were coordinated with PMIP3 to examine the coupled model responses to distinct external forcing. FGOALS contributed to PMIP3 by performing two core experiments of the mid-Holocene (6 ka) and Last Interglacial Maximum (LGM, 21 ka) and one Tier1 experiment of the mid-Pliocene (3 Ma). In the mid-Holocene, changes in the earth's orbital parameters play the dominant role in shaping climate changes by regulating insolation and seasonality (Zheng WP et al., 2013a). The LGM is affected by lower CO_2 concentrations and changes related to ice sheet extension (Zheng WP and Yu YQ, 2013b). In the mid-Pliocene, the CO_2 concentration exceeds 400 ppmv, which might be considered an analogous scenario for present-day and future climate projections (Zheng WP et al., 2013c).

The SAT simulated by FGOALS for the LGM and mid-Holocene is shown in Figure 12. In general, the results from FGOALS resemble the multi-model means in both the pattern and amplitude of the changes. The summer warming over mid-high latitudes in the Northern Hemisphere in response to the increased insolation during boreal summer was well captured. Note that the heat capacity is larger in the ocean; the SAT over the ocean shows slight weakening that leads to an enhanced land-sea thermal contrast and favors the strengthening of the monsoon system in the Northern Hemisphere. In LGM simulations, strong cooling occurs at high latitudes and regions covered with LGM ice sheets. The cooling is weaker over the tropics and ocean. FGOALS is also capable of reproducing large-scale changes in SAT, as shown in the paleoproxy data. As a result of high CO_2 concentrations, the SAT warms by approximately 1°C–2°C and 1°C–5°C over the ocean and continents, respectively. The SAT warming increases gradually from the mid to high latitudes, reaching a maximum over Greenland, the Arctic, and the Antarctic regions (figure not shown).

To better understand the position of 20th-century climate warming in the past millennial climate evolution and reduce the uncertainties of the simulations based on specific models, CMIP5 has developed an international collaboration for simulation of the past millennial climate as part of WGCM's long-term modeling activities for the IPCC AR5 (Zhou TJ et al., 2011). The LASG/IAP climate system model FGOALS has been involved in the past millennial climate simulations coordinated by CMIP5 (Man WM and Zhou TJ, 2011; Zhou TJ et al., 2011; Zhou XJ et al., 2011; Zhang J et al., 2013; Man WM and Zhou TJ, 2014a). Both the solar irradiance and volcanic forcing data used in driving the model are from Crowley et al. (2003). The effect of volcanic eruptions is applied as a negative deviation from the solar radiation. The latitudinal dependence of volcanic aerosols was not taken into account in this simulation, although more recent simulations have incorporated the effects of volcanic eruptions in a sophisticated manner. The greenhouse gas concentrations (CO_2, CH_4 and N_2O) are from Ammann et al. (2007). The influence of tropospheric sulfate aerosols

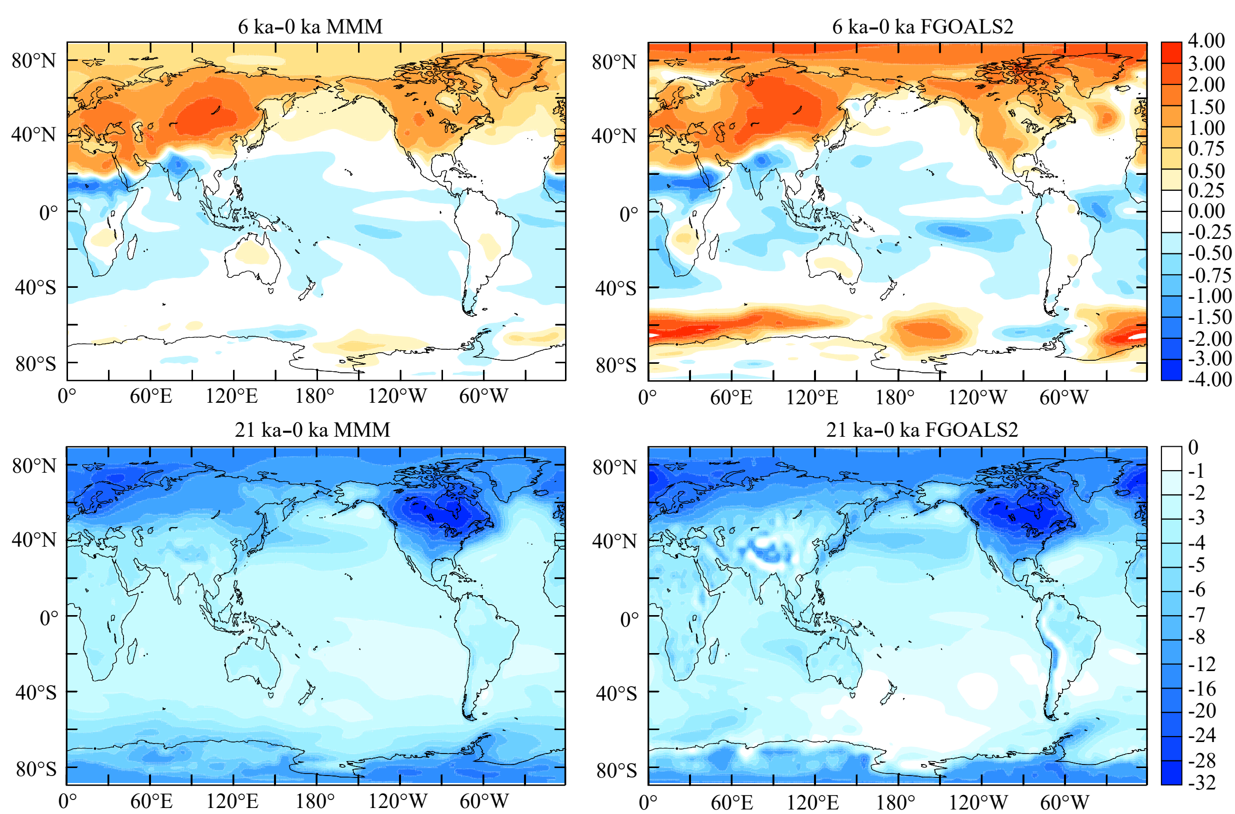

Figure 12. The surface air temperature (SAT) simulation by FGOALS for the paleoclimate simulation of the mid-Holocene (6 ka, above) and Last Interglacial Maximum (21 ka, below). MMM denotes the multi-model mean. Unit: °C (after Zheng WP et al. 2013b).

since AD 1850 is taken into account; the aerosol data are from CMIP3 (Zhou TJ and Yu RC, 2006). In comparison with the successful simulation of 20th-century global warming, successful simulation of the past millennial climate change is technically more difficult because the relatively weak change of external forcing during the natural variability periods is a challenge for the model (Zhou TJ et al., 2011).

The simulated North Hemispheric (NH) mean SAT changes during the past millennium are presented in Figure 13. The background shading represents the concentration of overlapping NH reconstructions, and the uncertainties are large at the beginning of the millennium. The decreasing availability of proxy sources and the deterioration of some proxy data back through time may be responsible for the inter-reconstruction variability. The simulation shows an NH temperature evolution comparable to those of the reconstructions. The solar minima Sporer (AD 1450–1540), Maunder (AD 1645–1715), and Dalton (AD 1790–1820) are clearly visible in the simulation. The warmth at the end of the 20th century is unprecedented in the context of the past millennium. There are large uncertainties at the beginning of the millennium, which can be attributed to the weak model sensitivity to natural forcing in FGOALS (Guo Z and Zhou TJ, 2013).

The simulated centennial-scale EASM variations in FGOALS display stronger EASM circulation during the warm epochs than during the cold epochs. The corresponding rainfall anomalies include excessive rainfall in the north but deficient rainfall in the south (Man WM and Zhou TJ, 2014a, figure not shown). The results from FGOALS are consistent with the reconstruction from stalagmite records (Zhang et al., 2008) and model results from the MPI Earth system model (Man WM et al., 2012). Volcanic eruptions are known to be a leading cause of natural climate change during the past millennium. Response of the EASM to volcanic aerosols in FGOALS indicates a weakening of the monsoon circulation, and the corresponding summer rainfall exhibits a coherent reduction over the entire East China region, which can be attributed to the decrease of moisture vapor from the tropical oceans (Man WM and Zhou TJ, 2014b).

While the CMIP5 models including FGOALS have been useful tools in projecting future changes of global monsoons, a spread is seen among the CMIP5 models (Kitoh et al., 2013; Christensen et al., 2013). The FGOALS model has been used to understand the uncertainties of future climate change projection. For example, East Asian summer climate is dominated by the western Pacific subtropical high (WPSH). But the projection of WPSH remains inconclusive (He C and Zhou TJ, 2015; He C. et al., 2015, 2017). While some CMIP5 models projected an enhanced WPSH, others projected a weak or even weakened WPSH (He C and Zhou TJ, 2015). To reveal how the different projected changes of the WPSH affect the monsoon rainfall over eastern China, composite changes in the precipitation and 850 hPa winds are shown for the P-type (with enhanced WPSH) and N-type (with weakened WPSH) models (Figure 14). Under both RCP4.5 and RCP8.5 scenarios, the northern part of eastern China witnesses an increased precipitation along with enhanced southerly wind following an enhanced WPSH, while decreased precipitation and weakened southerly wind are seen following a weakened WPSH, demonstrating the prominent role of the WPSH in controlling the rainfall pattern over the eastern China. Why did CMIP5 models show large spread in the projection of WPSH changes? Further diagnostic analysis revealed that the projected change in the WPSH intensity is dominated by the change in the zonal Sea Surface Temperature (SST) gradient between the tropical Indian Ocean (TIO) and the tropical western Pacific. A stronger (weaker) warming in the TIO favors an enhanced (weakened) WPSH. The CMIP5 models show spread in projecting the zonal SST gradient between the TIO and tropical western Pacific.

Climate sensitivity is an important metric of a model's response to greenhouse gas forcing. Uncertainty in climate sensitivity ac-

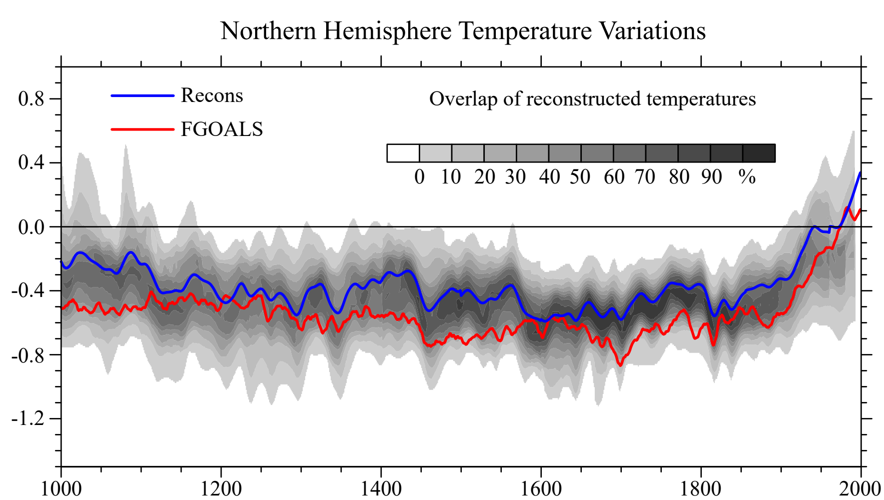

Figure 13. Low-pass filtered North Hemispheric (NH) mean surface temperature changes (°C) during the past millennium. The mean of the reconstructions is shown as the blue line, and the simulated time series is shown as the red line. The gray shading indicates the overlap of the uncertainty ranges of the NH reconstructions, as in Figure 6.13d of IPCC AR4 (Jansen et al., 2007). The anomalies are calculated with respect to the climate mean of the 1961–1990 reference period. Fluctuations at time scales less than 30 years have been removed (redrawn based on Man WM and Zhou TJ, 2014a).

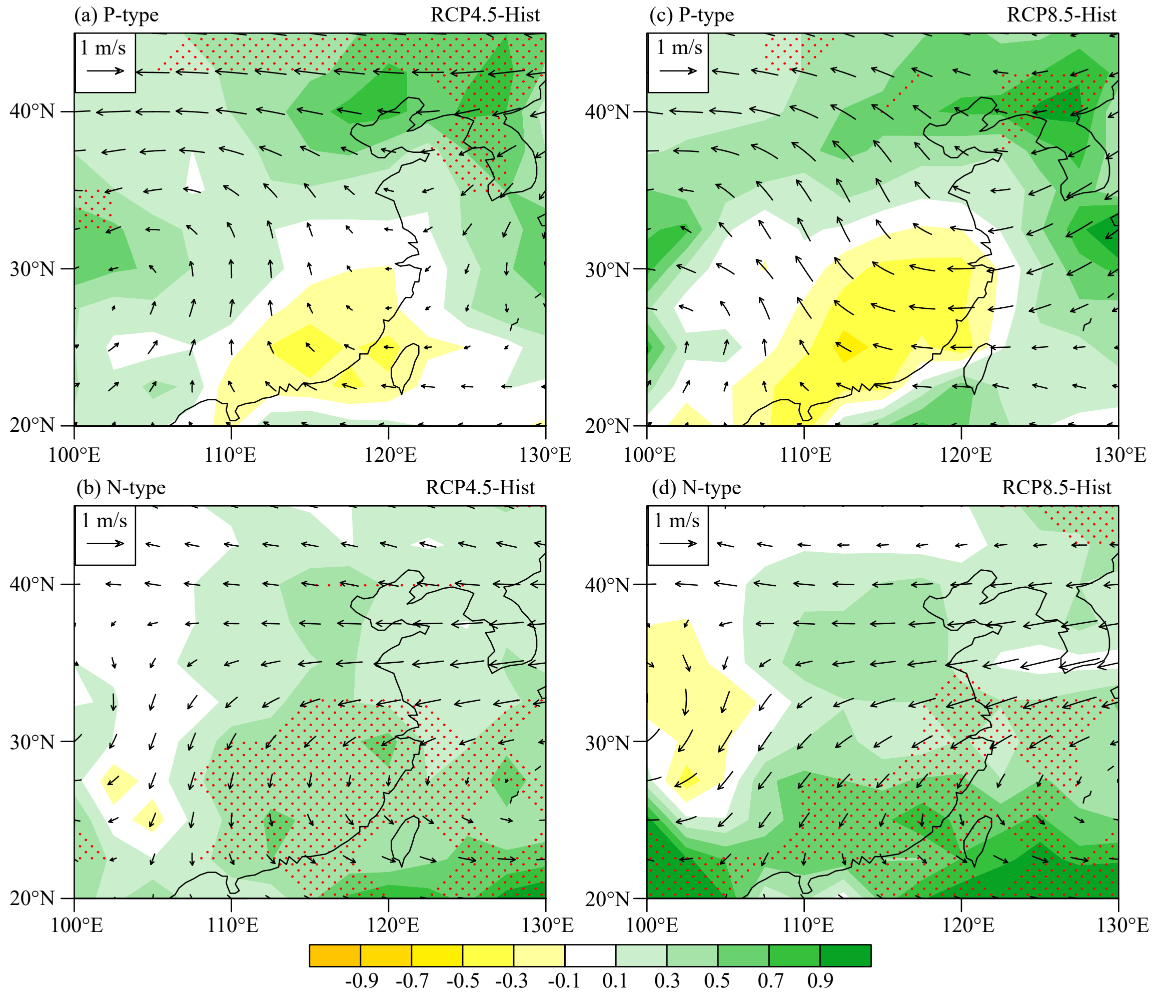

Figure 14. (a) P-type models' composite of the projected changes in precipitation (shading, unit: mm/day) and 850 hPa wind (vectors, unit: m/s) under the RCP4.5 scenario. (b) Same as (a) but for the N-type models. (c–d) Same as (a–b) but under the RCP8.5 scenario. The models that project significantly enhanced (decreased) western North Pacific subtropical high intensity are referred as P-type (N-type). The red dots indicate regions for which all of the P-type (or N-type) models agree in the sign of changes in precipitation (after He C and Zhou TJ, 2015).

counts for a large part of model spread in future projection (Zhou TJ and Chen XL, 2015; Chen XL and Zhou TJ, 2016). The two versions of the FGOALS model allow a good comparison to investigate the reasons for differing climate sensitivity and its possible effect on climate projection. In a standard analysis framework of climate feedback, the two versions of FGOALS show distinct climate sensitivity. FGOALS-s2 has higher climate sensitivity than FGOALS-g2 due to its stronger positive sea ice albedo and water vapor feedbacks (Chen XL et al., 2014; He B, 2016). As a result, in projection of the South Asian summer monsoon (SASM) under the RCP8.5 scenario, the two versions of FGOALS show distinct results among the total 35 CMIP5 models. The projected weakening of SASM circulation in FGOALS-s2 is much stronger than that in FGOALS-g2 and is nearly the strongest one across the 35 models (Chen XL and Zhou TJ, 2015). The higher climate sensitivity of FGOALS-s2 leads to a warmer equatorial Pacific, especially in the central-eastern part, which decelerates the Walker circulation and yields a shallower monsoon trough. Furthermore, more convective heating over the upper tropical troposphere in FGOALS-s2 reduces the meridional thermal contrast over the SASM region and atmospheric baroclinicity. Both of these phenomena cause weaker SASM circulation in FGOALS-s2 projection than in FGOALS-g2 projection. In contrast, despite weaker circulation, more SASM rainfall is projected in FGOALS-s2 due to a larger water vapor supply, which is also attributed to the higher climate sensitivity and stronger water vapor feedback in FGOALS-s2 (Chen XL and Zhou TJ, 2015).

5. Concluding Remarks

As an achievement of teamwork in LASG/IAP, the FGOALS2 model has shown encouraging performance in the aspects of cloud distribution and cloud radiation simulation, ENSO phenomena, and the Atlantic Meridional overturning circulation. The participation of FGOALS2 in CMIP5 has resulted in significant contributions to the IPCC WG1 AR5. Nonetheless, participation in CMIP and contribution to IPCC reports are not the sole purposes of model development within LASG/IAP. The fully coupled climate system model developed by LASG/IAP has served as a useful modeling tool or platform for promoting interdisciplinary climate research in China. In recent years, the FGOALS model has been applied to a variety of scientific studies and has supported the implementation of many national-level research projects, such as the National Program on Key Basic Research Project and National Natural Science Foundation projects. The FGOALS model has also contributed to the National Climate Change Assessment Report of China.

The FGOALS model is also hoped to be used in addressing some emerging new issues of climate change, such as the Paris Agreement of 2015, which aims to "limit global warming to below 2°C and pursue efforts to even limit it to 1.5°C relative to pre-industrial levels". Understanding the avoided impacts of 0.5°C less warming is a new scientific question to climate modeling community (Zhou TJ et al., 2018a, b). We acknowledge that the response of our FGOALS team is not as prompt as some world leading climate modelling centers such as the National Center of Atmospheric Research (NCAR) in addressing such kinds of challenging and new climate change sciences by designing warming targets driven scenarios and projections (Nangombe et al., 2018; Li DH et al., 2018). Lab-level or institute–level coordination of super computer resources are needed to foster such kinds of pioneering numerical experiments.

For the future development of IAP/LASG climate models, as part of the development of Earth system modeling platforms of the Chinese Academy of Sciences, more effort should be devoted to the coupling of Earth system models with integrated assessment models. Compared to the development of climate system models, the development of integrated assessment models in China is weak. The mitigation studies need the support of integrated assessment models. The coupling of climate system models with integrated assessment models has been highlighted by the international community. For example, the International Council for Science has proposed the Future Earth Project, which is a new international initiative on Earth system research for global sustainability. Earth system modeling is listed as one of the eight proposed crosscutting capabilities under the framework of Future Earth (Wang CY et al., 2015). Successful implementation of the Future Earth Project depends in part on continuing progress in the development of Earth system models and integrated assessment models.

Acknowledgments

This work was jointly supported by the National Natural Science Foundation of China (Grant No. 41330423, 41420104006 & 41530426) and the International Partnership Program of Chinese Academy of Sciences under Grant No. 134111KYSB20160031.

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